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Modeling changes in summer temperature of the Fraser River during the next century

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Summary The Fraser River basin in British Columbia has significant environmental, economic and cultural importance. Healthy river conditions through sufficient flows and optimal temperatures are of paramount importance for the survival of Pacific salmon, which migrate upriver toward the headwaters to spawn near the end of their lives. Trends have been detected which indicate that the annual flow and summer temperature have been increasing since the middle of the last century. In this study we examine the observed trend in summer temperature of the Fraser River and compare it with temperatures calculated as part of a global climate model (GCM) simulation in which atmospheric greenhouse gases are increasing. We then use the GCM to consider how these trends might continue through the present century. Both the observations and model indicate that during the last half of the 20th century, the summer temperature near the river mouth has been increasing at a rate of approximately 0.12 °C per decade in August. In this study we use an online method in which river temperatures are calculated directly as part of a GCM simulation and project how summer temperature near the mouth of the Fraser River might change by the end of the present century. The results indicate that between 2000 and 2100 river temperatures will increase in all summer months with a maximum increase of 0.14 °C per decade in August. This result is consistent with an offline modeling study by [Morrison, J., Quick, M.C., Goreman, M.G.G. 2002. Climate change in the Fraser River watershed: flow and temperature projections. *Journal of Hydrology*, 263, 230–244] in which they used output from two GCMS to drive a hydrologic model and predict future changes in river temperature and supports their contention that the timing and magnitude of the increase could be crucial for salmon migration. Future work can extend this analysis to other river systems in an effort to project the potential effects of climate change on

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the behavior of the world's large river basins, as well as identify the potential biological effects that may accompany these changes.

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Introduction

While evidence supporting the effect of human activities on the Earth's climate continues to strengthen (IPCC, 2001; IPCC, 2007), there are still many uncertainties in how these changes will be manifested and what their impacts will be. The 2001 IPCC report states that global surface air temperature (SAT) has risen $0.6 \pm 0.2^\circ$ over the last century, and increases will likely be larger through the end of the current century.

In addition to new climate patterns, there will also be changes in other components of the Earth system, such as alterations to the hydrologic cycle and intensity of storm systems and the subsequent biological and ecological effects. While the spatial and temporal effects of climate change on biological systems are difficult to quantify and future projections are uncertain, efforts must be undertaken to forecast the general behavior of these global systems under different future climate scenarios in order to prepare for a world that relies heavily on goods and services provided through climatically dependent natural resources.

The availability of freshwater resources is one example of an economic and health issue that will become increasingly important in coming decades. Therefore, assessing how freshwater resources from surface sources might change in the future is important and will require the use of global climate models. Since rivers serve as the primary conduit for transporting water and materials from land to the oceans, it is important to understand how these transports might change in the future. The hydrologic cycle is also a significant factor in climatic evolution as greenhouse gases continue to accumulate in the atmosphere (Loaiciga et al., 1996). As such, temperature fluctuations may influence many hydrologic factors, including the timing and magnitude of snowmelt runoff, the relationship between land cover and river flow, and the general mechanisms governing the movement and distribution of water across several scales. Several studies have investigated the potential hydrologic changes at various spatial and temporal scales that may result from climate change (Panagoulia and Dimou, 1997; Loaiciga et al., 1996; Miller and Russell, 1992; Arora, 2001; Arora and Boer, 2001; Morrison et al., 2002; Ye et al., 2003). Peterson et al. (2002) showed that these changes could be more prominent in Arctic regions (Peterson et al., 2002), particularly in summer months.

One example of a hydrologic system with important economic benefits is the Fraser River watershed, which is the largest Canadian river to discharge into the Pacific Ocean. The purpose of this paper is to examine the (limited) historical temperatures for the Fraser River for the last 60 years and project how they might change in the future. We take advantage of a new feature in the Goddard Institute for Space Studies (GISS) GCM that allows for the direct online calculation of river temperatures through the year 2100. This allows river temperatures to be calculated directly as

part of the global simulation. We compare our online results with the offline results of Morrison et al. (2002). Some of the characteristics of the Fraser River basin are discussed in the next section. The climate model is described in the description of the NASA-GISS GCM section. The results for the 20th century are given in observed and modeled summer temperature and flow (1940–2000) section, and the projections for the 21st century are given in observed and modeled summer temperature and flow (1900–2100) section. A discussion and conclusions are found in the discussion and conclusion section.

Fraser River basin

The Fraser River in British Columbia has headwaters in the Jasper National Park region of the Canadian Rocky Mountains (Fig. 1). It has a basin area of approximately 217,000 km² and flows for 1370 km before discharging into the Strait of Georgia (Thompson, 1981). Most of the flow is dominated by snowmelt runoff in the spring. The Fraser River is an important component of the Canadian fisheries and aquaculture industries, as it is a major spawning ground for Chinook and Sockeye salmon, which account for a large percentage of Canadian Fisheries Stocks (Morrison et al., 2002). As the salmon complete their life cycle by returning to their geographic birthplace by migrating upriver to their spawning grounds, the temperature of the river plays an important role in their success, and ultimately the reproductive fitness of the species.

It has been demonstrated that there is a strong relationship between river temperature and salmon mortality; higher than normal water temperatures correlate with higher mortality rates (Morrison et al., 2002; Gilhousen, 1990). Warmer water speeds the metabolic rates, thus depleting their energy as they swim upstream, as well as increases their susceptibility to disease (Morrison et al., 2002). Water temperatures of 20 °C can negatively affect spawning rates (Gilhousen, 1990), temperatures remaining between 22 °C and 24 °C over the course of several days can be fatal for salmon (Servizi and Janzen, 1977), and above this range can cause death in hours (Bouke et al., 1975). Therefore, potential changes in river conditions, whether they are in timing, magnitude, or temperature, could have ramifications on the immediate and the long-term survivability of Pacific Northwest salmon, as well as many other species that comprise this important freshwater ecosystem.

Since changes in river characteristics should be anticipated in light of continued climate change, it is important to try to develop an understanding of how the associated natural resource base will be affected; in the case of the Fraser, this base is the health of the salmon population. Elevated river temperatures, earlier peak flows, and lower summer flows will all be factors in the success of the annual salmon migration. Morrison et al. (2002) performed an analysis which examined historic flows and temperatures in the

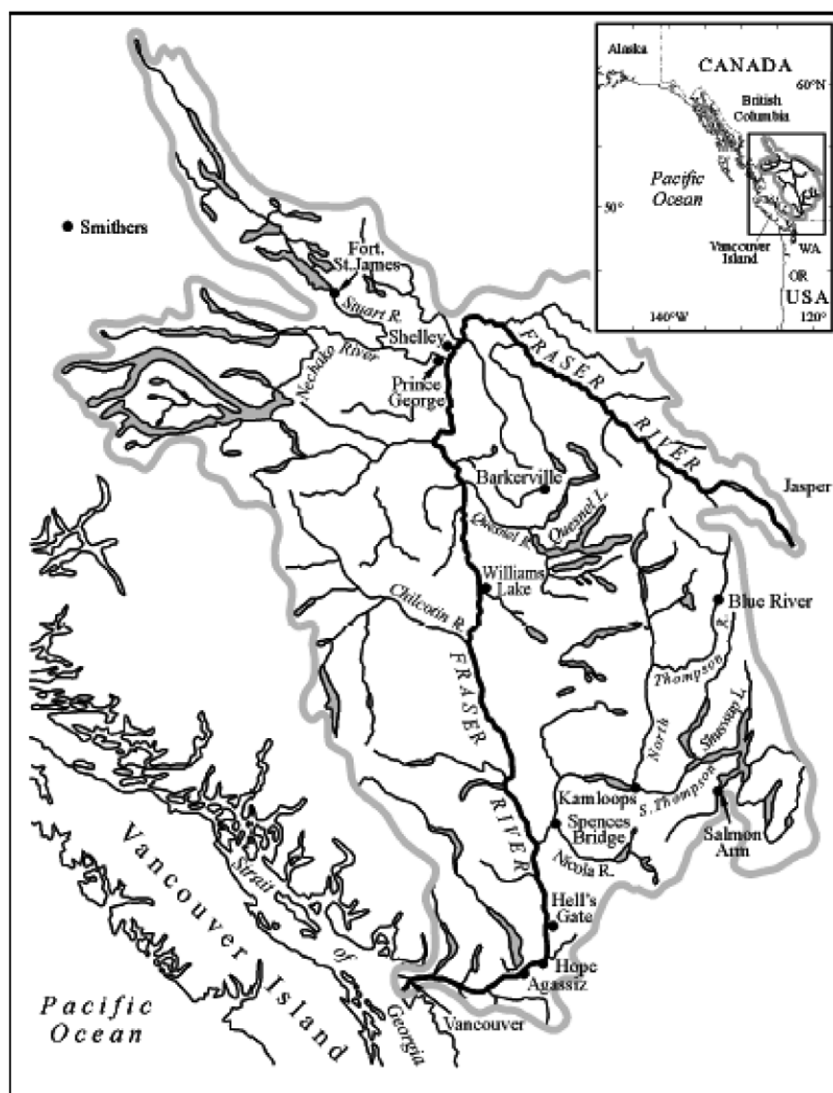


Figure 1 Map of the Fraser River watershed.

Fraser River throughout the 20th century. Their study determined that there were detectable trends in both the annual flow as well as in the summer river temperatures in the second half of the 20th century, and suggested a possible link with climate change. They report that peak flows that result from snowmelt runoff are occurring earlier in the year (0.11 days and 0.09 days earlier each year for one half and one third annual volume, respectively) between 1913 and 2000, and that mean summer river temperatures have been increasing at a rate of .22 °C per decade from 1953 to 1998 (Morrison et al., 2002). The observed river temperature increase is approximately 0.11 °C per decade when examined from 1942 to 2001 (this record is partially incomplete as some of the early years are missing data).

Morrison et al. (2002) extended the summer temperature trends of the Fraser River through the 21st century by down-scaling output generated from two global climate models (the Canadian Centre for Climate Modelling and Analysis model (CGCM1) and the Hadley Center for Climate Prediction and Research Model (HadCM2)) to sites in the Fraser River watershed. Using an offline approach they then used

the GCM output to drive a regional watershed model to predict future changes in river flow and temperature at a site near the mouth of the river. They were particularly concerned with the effects on salmon spawning in summer.

Description of the NASA-GISS GCM

The version of the GISS global coupled atmosphere–ocean–ice model used here has been used for the IPCC Fourth Assessment Report simulations, the previous version of which was described in Russell et al. (1995). Both the atmosphere and ocean use the C-grid numerical scheme of Arakawa and Lamb (1977) to solve the momentum equations. The base model resolution is $3 \times 4^\circ$ in latitude and longitude with 12 vertical layers in the atmosphere and up to 16 in the ocean. The atmosphere and ocean are coupled synchronously every hour. The atmospheric model uses Russell and Lerner's (1981) linear upstream scheme to advect potential enthalpy and water vapor. All significant atmospheric gases and aerosols are used to calculate

the radiative source term. The GISS ocean model has a free surface, employs the linear upstream scheme for the advection of heat and salt, and uses the K-profile parameterization (KPP) of Large et al. (1994) for the vertical mixing. The model also calculates at each hourly time step the flow of mass, potential enthalpy, and salt through 16 narrow (sub-grid scale) straits in response to the oceanic pressure gradient between the grid boxes on either end of the strait. Freshwater is added directly to the ocean by net precipitation and/or river flow. There is a four-layer thermodynamic sea-ice model, and sea-ice advection is based on the scheme described in Miller and Russell (1997).

The model's Fraser River basin consists of three grid cells at $3 \times 4^\circ$ resolution. The total surface area of lakes and rivers in these cells is 4%. Lakes and rivers use the same variables and the two words are used interchangeably. Lakes/rivers contain an upper mixed layer and possibly a second layer whose masses and heat contents vary in time. Mixing between the two layers is calculated each time step based on stability and surface stress. The rate of change of mass, M , in the upper layer is given by

$$dM/dt = P + S + R_{in} - E - R_{out} + X \quad (1)$$

where t is time, P is precipitation, S is source runoff from the land fraction, R_{in} is input river flow, E is evaporation, R_{out} is output river flow, and X is mixing of mass from the second layer. The heat content, H , of the upper layer is given by

$$dH/dt = Q_p + Q_s + Q_{R_{in}} - Q_E - Q_{R_{out}} + Q_X + SW - LW - Q_H \quad (2)$$

where Q_p , Q_s , $Q_{R_{in}}$, Q_E , $Q_{R_{out}}$ and Q_X are the heat contents transported by the respective processes in Eq. (1), SW is incoming short-wave radiation, LW is outgoing long-wave radiation, and Q_H is the sensible heat flux. Source runoff comes from the land component of the same grid cell,

which consists of both surface and underground components.

River discharge is calculated directly as part of the model simulation using the river routing scheme of Miller et al. (1994). Over time, lake mass above the sill depth of a grid cell flows to its downstream neighbor and eventually to the ocean. The temperature of the upper layer of the river is given by

$$T = H/M \cdot C_p \quad (3)$$

where $C_p = 4185 \text{ J/kg } ^\circ\text{C}$ is the specific heat capacity of water. The river temperature, in turn, affects some of the heat flux terms in Eq. (2).

In this study we examine model simulations from 1850 to 2100. The simulations include a control with constant 1850 atmospheric composition and a GHG experiment with observed greenhouse gases and tropospheric sulfate aerosol burden from 1850 to 2003 followed by IPCC's SRES A1B GHG and sulfate scenario (considered a middle emissions scenario) to 2100 (<http://aom.giss.nasa.gov/IN/GHGA1B.LP>). Because models may have systematic biases, we obtain the temporal changes in climate variables (e.g., temperature, precipitation, river flow) by calculating differences between the GHG experiment and the 1850 control simulation.

Observed and modeled summer temperature and flow (1940–2000)

In this section we examine the observed and modeled summer flow and temperature for the Fraser River for the last half of the 20th century. Understanding the monthly, seasonal and inter-annual fluctuations in flow rate and temperature is important for a variety of industries ranging from aquaculture/fisheries management to power generation. Observed flows were obtained from the Institute of Ocean Sciences in British Columbia, Canada, and are compared

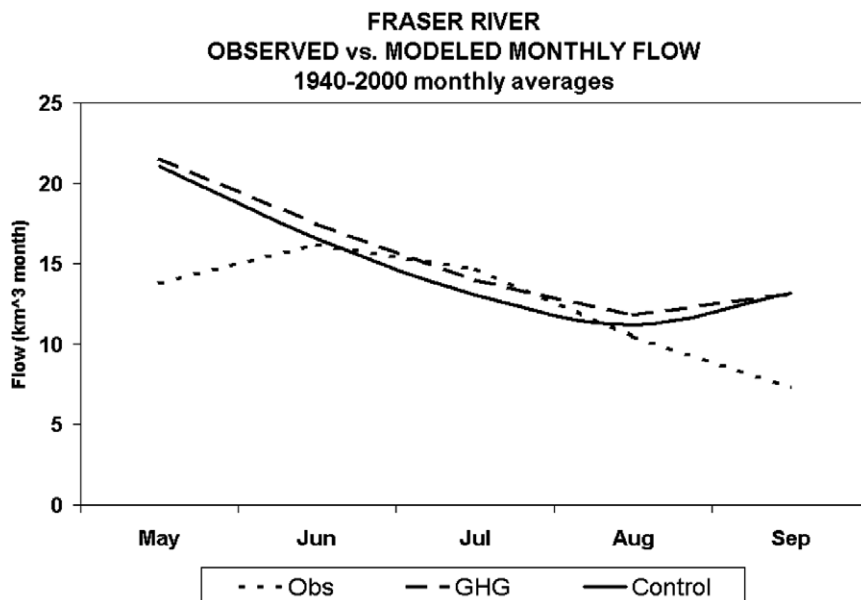


Figure 2 Fraser River, observed vs. modeled flow. 1940–2000 monthly averages.

to a control version of the model as well as a greenhouse gas (GHG) simulation that also includes the simulated effects of increasing sulfate aerosols.

In this study, there are three reasons for the focus on summer river temperatures. First, the ecological impacts on salmon are likely to be greatest in July and August. Second, the observed river temperatures are available only for summer months. And finally, the climate model does not simulate river flow very well in winter for the Fraser River. Although the model's precipitation is somewhat too high in all seasons, it is particularly high in winter. This causes the model's river flow in winter to be much higher than observed. However, since the Fraser is a small basin compared to other major global rivers, the outflow at the river mouth is not dependent on more than the previous month's conditions. For example, while July and August runoff in the Fraser basin is affected by June atmospheric conditions, it will not be affected significantly by conditions in April and May, as could be the case for a larger basin. Therefore, the model's poorly simulated winter flow is not a significant factor

when trying to examine how summer conditions might be affected by climate change.

Fig. 2 shows that the model's average monthly summer flow between 1940 and 2000 is in good agreement with the observed flow. Both observations and the GHG experiment indicate that the summer flow has been increasing during this period. As summer river flow is a significant factor in determining the ability of salmon to successfully migrate upstream to the spawning beds, it is important to examine it further in the context of future climate scenarios. While sufficient flow is vital, river temperature is also important for the reproductive success of northwest salmon. Daily river temperatures are available for the Fraser River for the period from July first through September 15th between 1942 and 2001 through the Canadian Fisheries Service, who were monitoring salmon spawning conditions during this period.

Fig. 3a and 3b shows observed average summer temperatures at Hell's Gate for the last 60 years based on Morrison et al. (2002). The temperatures were recorded for the

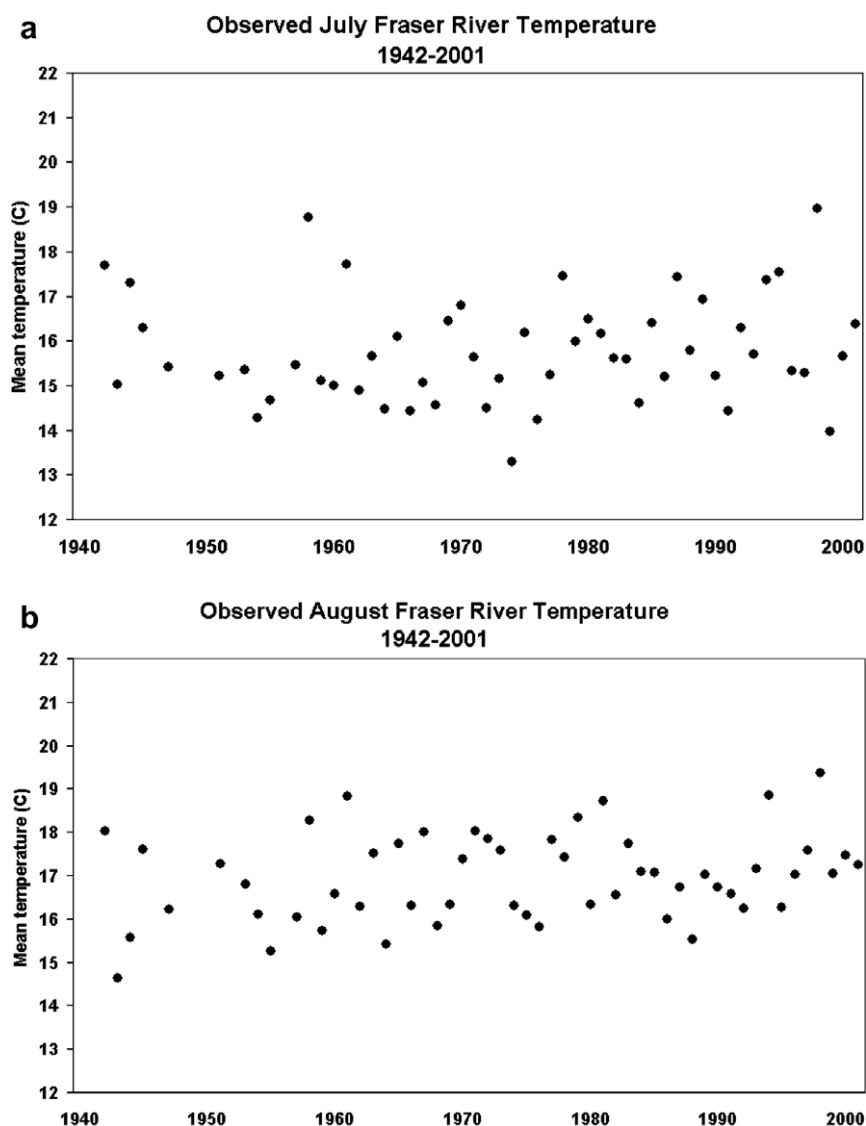


Figure 3 Observed Fraser River temperature from 1942 to 2001 for (a) July and (b) August.

period 1942–2001 and usually include daily temperatures from July 1st to September 15th because this is the most crucial period for upstream salmon migration. Some data are missing from the earlier years. Fig. 3 shows that there are positive temperature trends in both July and August ($+0.07^{\circ}\text{C}$ and $+0.15^{\circ}\text{C}$ per decade, respectively), more notably in August. The trends for both months are statistically significant at 99%. The observed average river temperature recorded at the Hell's Gate station from 1942 to 2001 was 15.77°C in July and 16.95°C in August. Not only will increasing surface air temperature raise the river temperature, but it will also affect the timing and magnitude of snowmelt runoff, which in turn will have ecological ramifications. According to Foreman et al. (2001) who analyzed flow from a gauge in the town of Hope (see Fig. 1) from 1912 to 1998, peak flow for the Fraser is occurring earlier in the year. Among the report's notable findings:

- The Julian day marking 1/3 and 1/2 of the annual cumulative flow is occurring earlier (equivalent to 11 and 9 days per century, respectively),
- Peak flow arrives earlier in the year after El Niño events, and
- Total river flow tended to be higher following a La Niña winter.

The report states that we can assume that as climate changes, the trend in earlier peak flows and lower summer flows is likely to continue.

A comparison of modeled and observed temperatures for July and August is shown in Fig. 4a and 4b and in Tables 1 and 2. The observed monthly average temperatures in Table 1 are based on daily temperatures. The July and August observations are compared to the model's monthly temperatures. The GHG version of the model shows a small in-

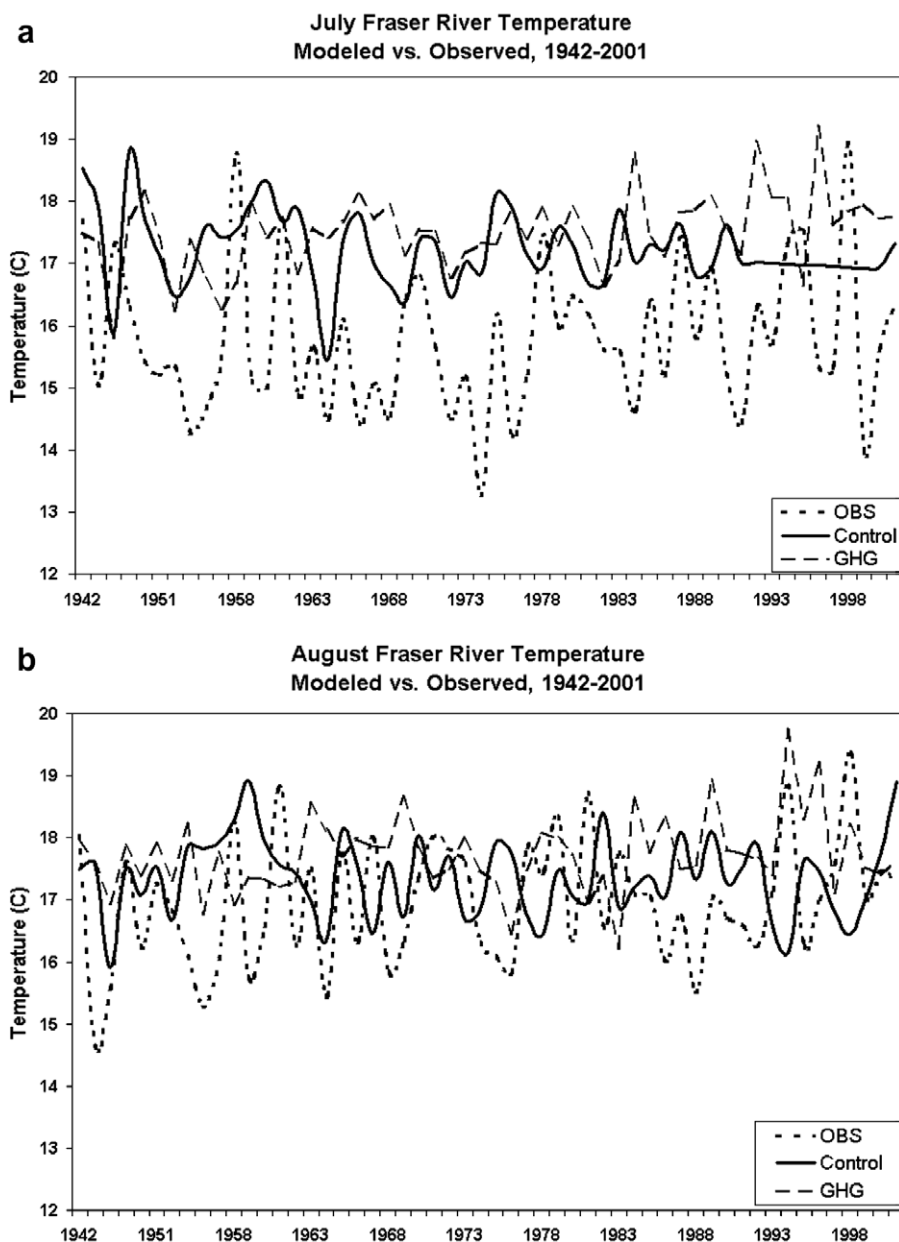


Figure 4 Modeled vs. observed Fraser River temperature from 1942 to 2001 for (a) July and (b) August.

Table 1 Observed and GCM statistics, 1940–2001

	July			August		
	Observed	Control	GHG	Obs	Control	GHG
Average temperature	15.77	17.22	17.51	16.95	17.37	17.72
Low temperature	13.29	15.45	15.79	14.64	15.91	16.21
High temperature	18.96	18.82	19.22	19.36	18.92	19.76
High departure from mean	3.19	1.59	1.71	2.41	1.55	2.04
Low departure from mean	2.48	1.78	1.72	2.31	1.46	1.51
Number of occurrences when average temperature > 18 °C	2	4	8	9	8	12

Table 2 Fraser River temperature changes (C) per decade for observations and model output, 1940–2001

	July	August	JulAug average
Observed	0.07	0.15	0.11
Control	−0.09	−0.02	−0.06
GHG	0.16	0.09	0.13

crease (statistically significant at 95%) for both July and August, which is similar to the observed, while there is little trend in the control run. The mean temperatures of the model are somewhat too high in July but in quite good agreement with the observed temperatures in August. It should be noted that river flow and temperature in the model are not tuned to specific river basins but are set according to global criteria. This provides evidence that the model does a good job of simulating summer temperatures of the Fraser River and provides confidence that we can extend these projections to the end of the century. In the control run for both months, Fig. 4a and 4b shows that the modeled temperatures are in the same range as the observations. The increasing trend in the observed and GHG temperatures during the referenced time periods are statistically significant at the 95% and 98% confidence levels. Table 2 shows that both the observed and GHG modeled temperatures exhibit an increasing trend in July and August, and more significant deviations above 18° are apparent in the most recent years. As maximum temperature is an important factor regarding salmon migration, this could provide some insight on how the salmon migration and subsequent spawning rates could be affected under future climate scenarios.

Observed and modeled summer temperature and flow (1900–2100)

As an increasing trend in river temperature is evident during the time period examined in the previous section, we will examine the model simulation to see how river temperature might change during the present century. First, however, we examine the summer flow during this period. Fig. 5 shows temperatures from the control and GHG simulations for July and August from 1900 to 2100. If we examine the control and GHG simulations separately for the first and second 100 years, both the extremes and range are similar between 1900 and 2000. However, during the second 100 years of this comparison (2001–2100), there is a significant increasing trend in the GHG temperatures, and the extreme

flows are significantly higher than those generated by the control version in both July and August. The likely cause of the higher flow through 2100 is that the GHG model generates more precipitation over the basin as a result of a warmer atmosphere. This leads to a more active flow pattern under simulated future warming conditions.

Arora and Boer (2001) used output from the Canadian Center for Climate Modeling and Analysis coupled general circulation model (CGCM) to compare modeled flow using a control and GHG enhanced version for the years 2070–2100 for 23 large river basins globally. As part of their analyses, they examined the percentage change in simulated discharge between control and GHG versions of the model. Their results showed that in middle and high latitude river basins, seven out of ten rivers exhibited an increase in mean annual discharge when the GHG projections were compared with the control during this 30-year period. For example, the Mackenzie River showed a 20% increase in mean annual discharge, the Yukon River produced a 10% increase, and the Columbia River produced a 67% increase. Interestingly, in their study only one of the 13 tropical and low latitude rivers (Ganges River) produced an increase in mean annual discharge over the same period. With respect to the middle and high latitude projections, our findings for the Fraser River are consistent with those of Arora and Boer that increased GHG concentrations enhance the hydrologic cycle and influence higher flow rates in similar geographic settings.

Fig. 6a and 6b shows the river temperature for July and August from 1900 to 2100. In both months, the control version contains a small negative drift in temperature. As noted with the flow comparison, the control and GHG simulations have similar values in the first half of this period, but the GHG simulation exhibits a significant increase in river temperature beyond 2030. For July and August the temperatures between 2075 and 2100 are approximately 2 °C higher in the GHG than in the control. Fig. 7 shows the annual cycle of monthly river temperatures between 2070 and 2100 for both the control and GHG simulations. In all months, the river temperature is higher by the end of the century, with July and August being the months most likely to exceed the 18 °C threshold. Since these are average temperature projections, June and September will also be important, as there will likely be cases of extremes on the high side in these months as well.

Discussion and conclusions

In this study we have used observations and a global climate model to examine how summer river temperatures and flow

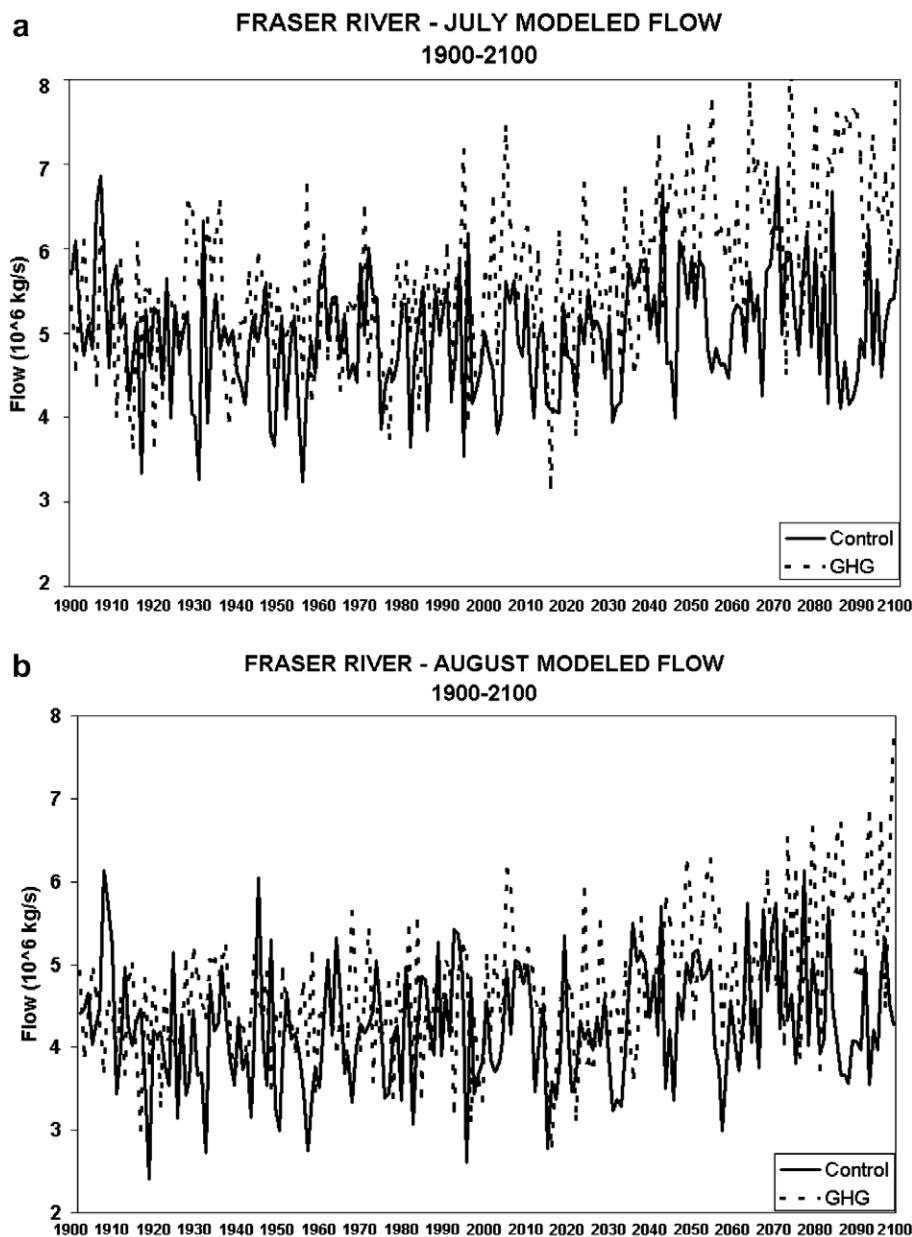


Figure 5 Modeled Flow for Fraser River from 1900 to 2100 for (a) July and (b) August.

of the Fraser River changed during the last half of the 20th century and might change by the end of the present century. Although the model did not replicate the annual winter flow well, it did agree with the observed mean summer flow between 1942 and 2000.

The observed river temperature at the Hell's Gate station on the Fraser River shows an increasing trend during the last half of the 20th century (1942–2001). The average temperature during this period is 15.77 °C in July, and 16.95 °C in August. The model's mean summer river temperatures are in good agreement with observations, particularly in August. During this period, the observed river temperatures increased at a rate of 0.07 °C per decade in July and 0.15 °C per decade in August. The temperatures in the model GHG experiment also increased, although at somewhat different rates, 0.16 °C and 0.09 °C per decade for July and August, respectively.

Since the model's summer flow and summer temperatures are close to observed values, we can use the control version as a baseline for how summer river flow and temperature might change under current greenhouse gas projections through the end of the 21st century. By extending this to the end of the 21st century, we can then start to assess how the hydrology of the Fraser River basin might be affected under future greenhouse gas scenarios and how these changes might affect river ecosystems.

We have used an online method in which river temperatures are calculated directly as part of the GCM simulation. The river temperatures, in turn, feed back into the model's heat flux calculations, although the feedback is likely to be small for the Fraser basin because the water surface is only 4% of the total area of the model cells. The GHG simulation shows how temperature near the mouth of the Fraser River might change by the end of the present century. The current

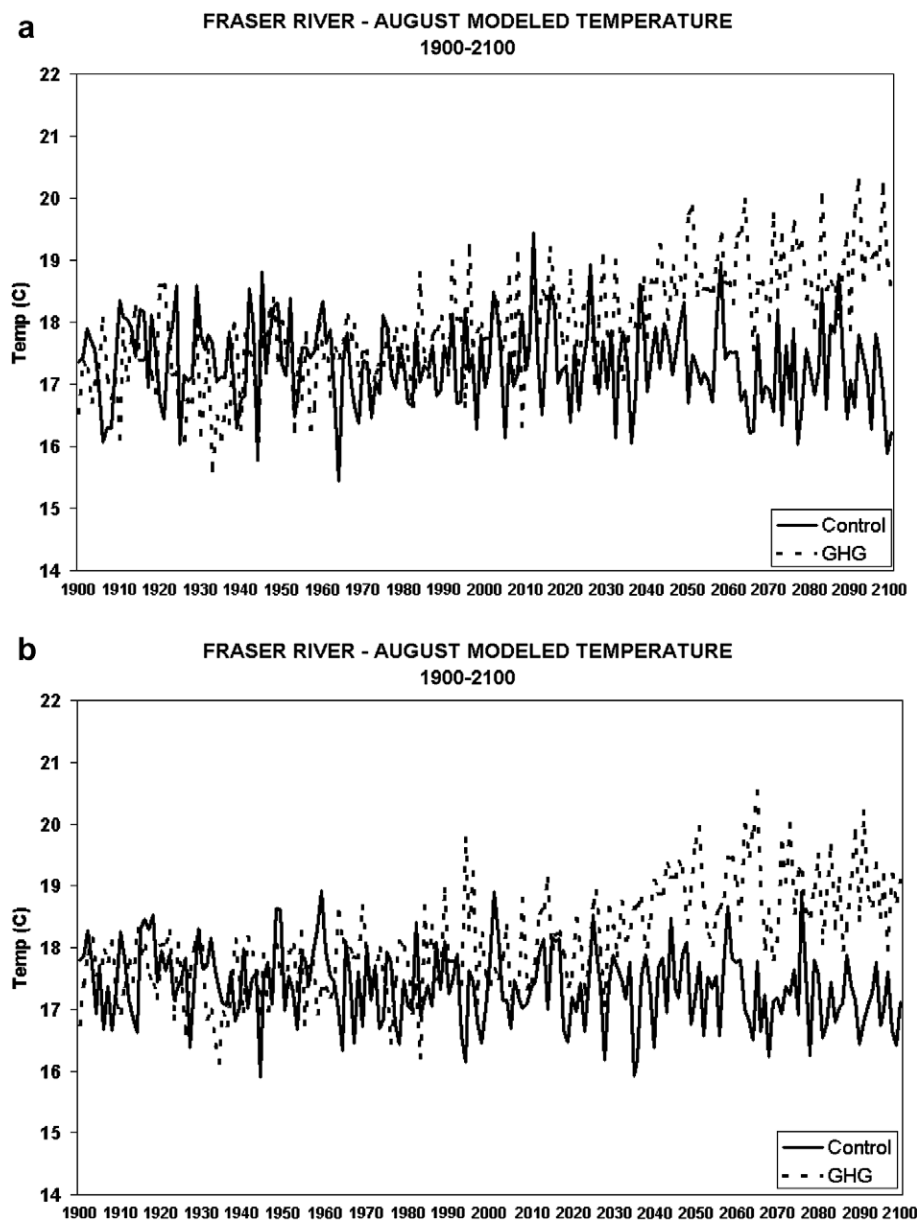


Figure 6 Modeled Temperature for Fraser River from 1900 to 2100 for (a) July and (b) August.

positive trends for warmer Fraser River temperatures and increased freshwater outflow are projected to continue and to significantly increase by the end of the century as shown in the GHG experiment. Most notable are the projected increases in river flow and temperature after 2030. The results indicate that river temperatures will increase in all summer months with the maximum increase of 0.14 °C per decade in August between 2000 and 2100. Although the focus here has been on summer months, the model indicates that by the end of the century river temperatures will increase in all months with little difference between seasons.

Morrison et al. (2002) performed an analysis which examined historic flows and temperatures in the Fraser River throughout the 20th century. They were particularly concerned with the effects of temperature change on salmon spawning in summer. They found detectable increases in both the annual flow as well as in the summertime river temperatures in the second half of the 20th century and sug-

gested a possible link with climate change. They also found that peak flows resulting from snowmelt runoff are occurring earlier in the year. Morrison et al. (2002) extended these temperature projections through the 21st century by downscaling output generated from two global climate models (the Canadian Centre for Climate Modelling and Analysis model (CGCM1) and the Hadley Center for Climate Prediction and Research Model (HadCM2)) to sites in the Fraser River watershed. Using an offline approach they then used the GCM output to drive a regional watershed model to predict future changes in river flow and temperature at a site near the mouth of the river. We have compared our online modeled temperature changes with their offline changes through the year 2100 and they are quite similar.

What will anticipated future temperature changes mean for the survival and fitness of mid-latitude and high-latitude, freshwater dominated ecosystems? Morrison et al. (2002) have discussed the potential impacts of increasing

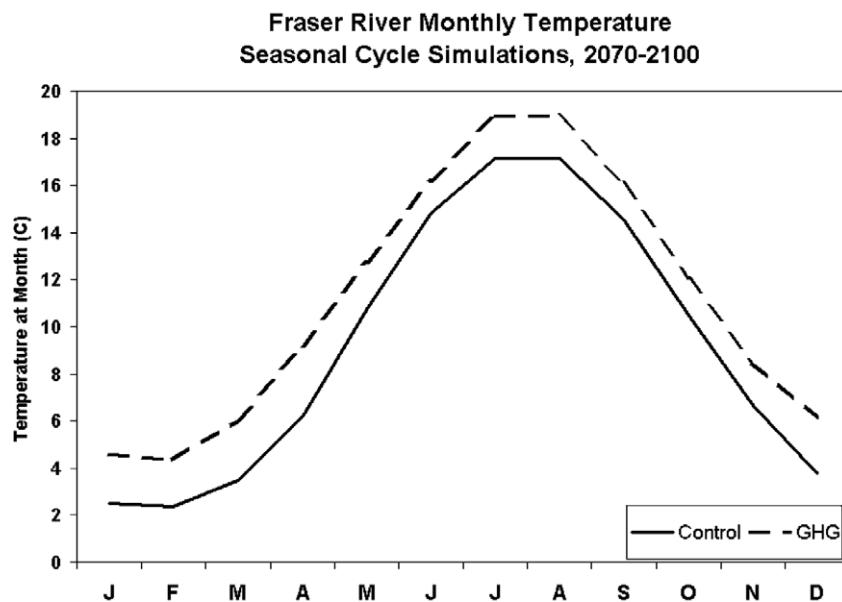


Figure 7 Fraser River monthly temperature, seasonal cycle simulations. 2070 to 2100.

temperature on salmon in the Fraser River. When the results here are extended through the end of the century, the projected rate of temperature increase, while seemingly small, may have significant impacts on the long-term fitness of the northwest salmon. Slower increases in temperature may provide the salmon with the opportunity to adapt to the changing physical conditions, and thereby reduce the potential negative impacts of temperature changes, and still allow for some level of reproductive success. But the rapid increases that the model projects in the latter portion of the 21st century may be too fast to allow organisms or communities to adapt physiologically or behaviorally. It is also important to remember that these projected river temperatures are average monthly values. Since extreme daily temperatures are not represented in our average monthly values, the modeled summer temperature increases may underestimate the impact on mortality in the future.

Although the results here provide some insight on how coarse scale models might be used to investigate specific biological effects, GCMs by their nature, are not intended to provide specific basin level characteristics where physical extremes (on spatial scales of kilometers and timescales of hours) can be the limiting biological factors. Future work should try to better assess and model the finer scale temperature variability (both spatial and temporal) and then link these physical conditions to ecosystem responses, such as the migration and spawning of salmon. This analysis can be extended to other river systems in an effort to project the potential effects of climate change on the behavior of the world's large river basins as well as to identify the potential biological effects that may accompany these changes.

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